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PERFORMANCE CHARACTERISTICS OF A CO2 WAVEGUIDE LASER,(U)
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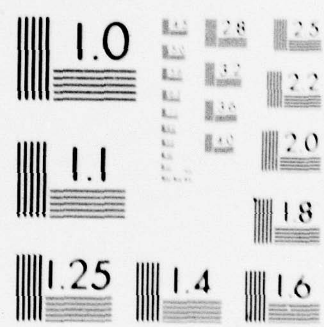

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LEVEL II

PERFORMANCE CHARACTERISTICS OF A CO_2 WAVEGUIDE LASER

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(6) PERFORMANCE CHARACTERISTICS

OF A

CO_2 WAVEGUIDE LASER

by

(10) P. Lavigne, G. Otis and D. Vincent

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RESUME

Nous avons développé un tube laser CO_2 à onde entretenue d'un diamètre de 2 mm, de construction robuste, et en avons analysé les caractéristiques. Nous avons observé que le gain à faible signal atteignait sa valeur optimale lorsque la pression partielle de CO_2 dans un mélange CO_2:Xe:He était d'environ 15 torrs et que cette valeur décroissait avec la concentration de CO_2. Le remplacement d'une partie du CO_2 par du CO améliorait de façon marquante le rendement du laser. Nous avons réussi à produire une puissance par unité de longueur de 0.18 W/cm à 110 torrs dans un mélange CO_2:CO:Xe:He de 10:20:4:66 dans une décharge de 9.5 cm de long. Tout indique que le rendement serait meilleur dans un tube plus long. L'utilisation d'un réseau comme miroir nous a permis de fixer l'orientation du champ électrique et d'augmenter le domaine de syntonisation de fréquence grâce à la réduction du nombre de raies émettrices. Dans l'état actuel du projet, nous avons fait fonctionner le laser en régime semi-scellé avec remplissage aux 300 heures. (NC)

ABSTRACT

A rugged CW CO_2 2-mm-diameter laser tube has been developed and its performance analyzed. It has been found that the small-signal gain was optimum when the CO_2 partial pressure in a CO_2:Xe:He mixture amounted to about 15 torr with the peak value decreasing with the CO_2 proportion. Replacement of part of the CO_2 by CO resulted in a significant improvement of the laser efficiency. A power extraction of 0.18 W/cm has been achieved at 110 torr with a CO_2:CO:Xe:He mixture of 10:20:4:66 in a 9.5-cm-long discharge. There are indications that a better extraction is possible in longer tubes. Use of a grating as one end mirror was sufficient to control the electric field orientation and led to a greater tuning range by limiting the number of oscillating lines. At the present stage, semi-sealed-off operation is possible with a filling period of about 300 hours. (U)

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1.0 INTRODUCTION

Heterodyne detection appears very promising in optical radar applications of the CO_2 laser and so has received much interest at DREV during the past few years (Ref. 1). Such type of detection requires the use of a stable, frequency-tunable laser source of compact size as the local oscillator. Oversized waveguide structures (Ref. 2) offer the possibility of constructing compact CO_2 oscillators operating at pressures sufficiently high to allow tunability over several hundreds of megahertz (Ref. 3).

In this report, we describe the design and analyze the performance characteristics of a CW waveguide CO_2 laser. Construction methods, small-signal gain, output power, signature and sealed-off lifetime have been studied to find optimizing conditions. Emphasis has been placed in miniaturizing and ruggedizing the laser enough to conveniently use it outside the laboratory. Even if the primary objective of this work was to design a heterodyne local oscillator, the laser has been found capable of sufficient power to make it suitable for many other types of applications.

The work done in this report was performed at DREV between January 1977 and December 1978 under PCN 33H04, Miniaturization of lasers.

2.0 CONSTRUCTION OF THE LASER

2.1 Laser tube

During the experiments with CO_2 waveguide lasers, many configurations and assembling techniques have been tried. Figure 1 illustrates the design that appears the most reliable and rugged. The laser tube was fabricated from a 99.5% pure beryllium oxide ceramic rod 2.5 cm in diameter and 12.5 cm long with a drilled axial bore of 2 mm (surface finish S20 microinches) as supplied by Consolidated Ceramics (Ref. 4). The high thermal conductivity and the optical constants of BeO make it a good candidate for CO_2 waveguide lasers (Refs. 5,6).

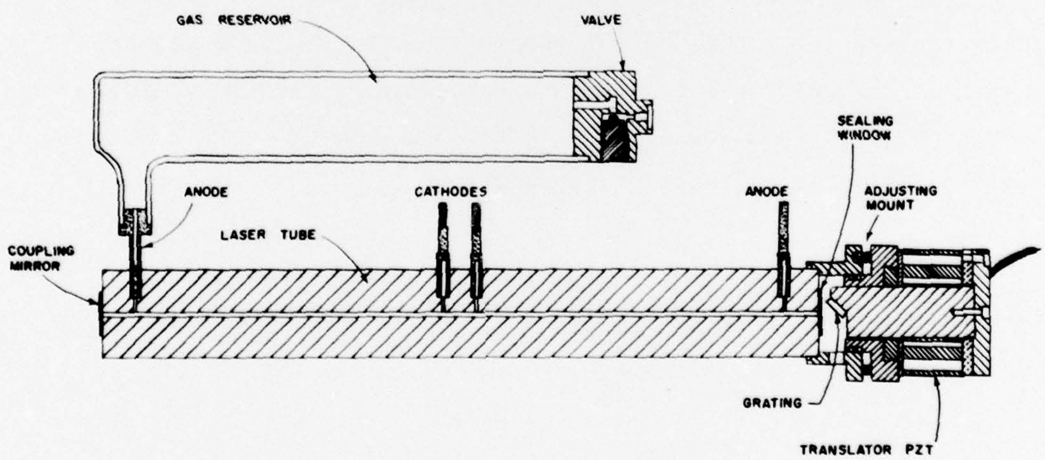

FIGURE 1 - Drawing of the waveguide laser tube

Four side holes were drilled radially into the bore to accept the electrodes as shown in Fig. 1. The 2 end holes were drilled at 1 cm from the tube ends whereas the other were spaced by 1 cm and positioned symmetrically about the tube center. This provided a pair of excitation discharges that are electrically in parallel and stabilized by individual 2-MΩ ballast resistors. The tube was then cleaned with hydrofluoric acid and baked at $1000^{o}C$ for 3 h before assembly. The total discharge length amounted then to 9.5 centimeters. The 90% Pt - 10% Rh cathodes were epoxied in the center holes to minimize sputtering damage to the end mirrors. Of the 2 anodes that were fixed in the end holes, one was drilled to serve as gas inlet from a 40-cm^3 glass reservoir. The latter was sealed with a miniature stainless steel valve of special design (Fig. 1) to allow quick replacement of the gas mixture. After mounting of the flanges, mirrors, electrodes and reservoir, the laser was pumped for ≈ 70 h with a diffusion pump, and helium-leak tested at a sensitivity of 10^{-9} atm-cm^3/second.

Excitation of this 4 electrode configuration can occur in different ways. When conducting flanges were used as mirror holders, a negative voltage was applied to the center cathodes through the two 2-MΩ ballast resistors. Because simultaneous striking is a random process, a major problem was to insure reliability in striking the pair of discharges and to avoid current flow between the cathodes. Furthermore, with insufficient ballast resistors, oscillating discharge occurred between the 2 cathodes. This led to a very rapid degradation of the tube due presumably to some deposit on the inner wall of the intercathode spacing. In particular, it was observed that roughly 5 unsuccessful attempts to strike both discharges resulted in a two-fold decrease in the output power of a new tube. Ballast resistors of 2 MΩ were sufficient to eliminate instabilities.

Reliable striking of both discharges can be achieved if the intercathode spacing is made large enough so that the electric field in this gap never exceeds that between either cathode and its corresponding anode (Ref. 7). In our configuration, this led to a cathode-cathode separation of the same order as the cathode-anode gap and, consequently, to an inefficient use of the volume.

Another approach to the problem lies in the use of the ballast resistors on the anode (end) sides. Although both ends of the tube are at high potential, that solution was finally adopted after designing a tube (Fig. 1) that allowed electrical isolation of the mirrors and prevented any high-voltage hazard. The use of 2 cathodes then becomes unnecessary and 3 electrode tubes could be used. However, as only tubes with 4 holes were available, the following experiments were conducted directly connecting the 2 center electrodes to the HV power supply and grounding the 2 end-anodes through 2-MΩ resistors.

2.2 Optical cavity

Propagation characteristics of such oversized structures have been extensively studied by Marcatili and Schmeltzer (Ref. 8). They have shown that when the tube material has a refractive index smaller than 2.02, the linearly polarized, axially symmetric hybrid EH_{11} mode is the lowest-loss propagating mode. This mode appears very attractive since over 98% of its energy is contained in the center lobe (Ref. 9). Furthermore, its transverse profile closely fits the open-resonator TEM_{oo} gaussian mode (Ref. 10) with a corresponding waist diameter of 64% the bore diameter (Ref. 11). The EH_{11} mode configuration has propagation losses given by (Ref. 8):

$$\alpha_{nm} = \left[\frac{\mu_{nm}}{2\pi}\right]^2 \frac{\lambda^2}{a^3} R_e (\nu_n)$$

where μ_{nm} is the m^{th} root of J_{n-1} (x); λ, the wavelength; a, the bore radius and ν_n, a function of the complex refractive index. Calculations for data (Ref. 6) based on the single-crystal BeO optical constant give a loss coefficient less than 5.4×10^{-6} cm^{-1} in a 2-mm ID BeO capillary. Measurements (Ref. 10) have shown losses smaller than 10^{-4} cm^{-1} in a drilled beryllia rod. In practice, however, the major loss sources are the camber of the tube and the lack of inner-wall smoothness. For example, it has been shown (Ref. 10) that even a 75-m curvature can double the losses of a 30-cm-long guide. Therefore, particular care must be taken to avoid any curvature of the rod and to insure that impurities are absent from the bore.

Hollow-waveguide-laser resonators have been studied by several authors (Refs. 9-13) and it has been demonstrated that 3 types of optical-resonator arrangements (waveguide-laser structure plus external feedback mirrors) can lead to low-loss situations that favor the oscillation of the EH_{11} mode (Refs. 11, 14). These low-loss configurations are:

1) Mirrors with a large radius of curvature with their center of curvature situated approximately at the guide entrance (e.g. R = 1 m for a 2-mm-bore tube).

2) Medium-radius-of-curvature mirrors separated by half their radius of curvature from the guide entrance (e.g. R = 25 cm for a 2-mm tube).

3) Flat mirrors close to the guide ends.

In applications where high power in the EH_{11} mode is required, configuration 2 appears particularly attractive as it inherently offers a good mode discrimination (Ref. 11). Furthermore, the first 2 arrangements give the possibility of enhancing this selectivity by aperturing the mirrors. However, a longer cavity and a narrower tuning range represent major drawbacks of these cavities.

For our local-oscillator application, the more convenient third configuration was chosen. The 96%-reflectivity ZnSe coupling mirror was epoxied directly on the tube end. Proper alignment was insured by continuously monitoring the mirror orientation with a He-Ne laser beam during the curing process. The other end of the tube was sealed with a 99.7% transmitting ZnSe window so that either a flat mirror or a grating could be used as the other optical cavity element. In that configuration, the losses of a 2-mm tube are approximately given by (Ref. 11)

$$\ell = 1.2d^{3/2}\%$$

where d is the distance between the tube end and the mirror. This second element was mounted on a PZT translator which was fixed to a mirror-orienting device made of isolating material. The spacing between the sealing window and the grating or high-reflectivity mirror was $\leq$ 5 mm so that less than 0.4% losses were expected at the mirror-tube interface. This assembly technique appears very rugged and allows electrical isolation of the tube ends. The anode can be at high potential and striking problems are relaxed.

3.0 GAIN MEASUREMENTS

For gain measurements, a frequency-stabilized CO_2 laser tuned to the center of the P(20) 10.6-μm transition was used to probe a 12.5-cm-long bore. The BeO capillary was similar to the waveguide described in Section 2.1 except for the end mirrors which were replaced by NaCℓ windows. The tube was water-cooled to about 17° C. The laser beam was chopped and detected with a pyroelectric sensor connected to a lock-in amplifier. The probe beam was coupled into the waveguide with a focusing lens. Gain results were obtained by measuring the difference between the input and the transmitted power with the amplifier discharge on and off. Care was taken to work at sufficiently low input power to avoid saturation effects.

The measured gain coefficient as a function of current at a total pressure of 60 torr is shown in Fig. 2 for 3 different CO_2:CO:O_2:Xe:He mixtures. During these measurements, the proportion of CO_2 + CO was kept constant at 30% while O_2 was added in the stoichiometric ratio. The concentration of Xe was fixed at 4% and He was added to complete the mixture. The gain was found nearly independent of the discharge current from 1.5 to 4 mA as already noticed by Abrams and Bridges (Ref. 6). Furthermore, the gain coefficient of the different mixtures was identical whatever the initial $[CO_2]/[CO_2 + CO]$ ratio as long as the relative pressure of CO_2 + CO was constant and O_2 was added in half the quantity of CO. Several measurements made at different pressures varying between 30 and 120 torr exhibited the same behavior. This indicates that CO_2 was dissociated in the discharge (Refs. 15-18):

$$CO_2 + e^- \rightleftarrows CO + \tfrac{1}{2} O_2 \qquad [1]$$

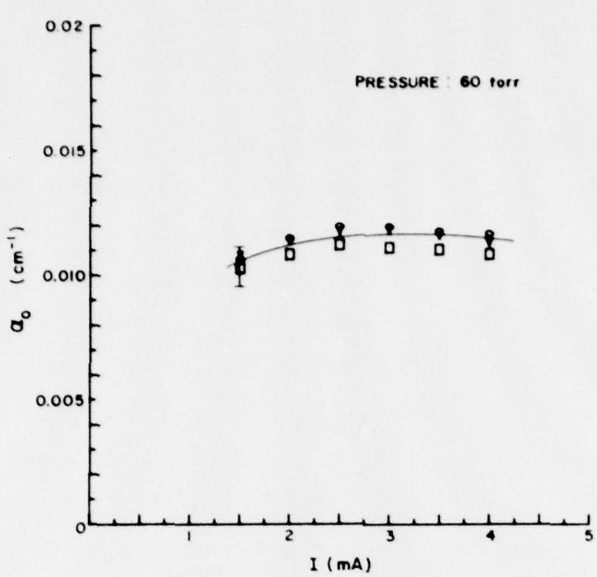

FIGURE 2 - Small-signal-gain coefficient versus current for various CO_2:CO:O_2:Xe:He sealed-off mixtures: o [30:0:0:4:66], □[20:10:5:4:61] et ∇ [10:20:10:4:56]. The proportion of CO_2 + CO was kept constant at 30%.

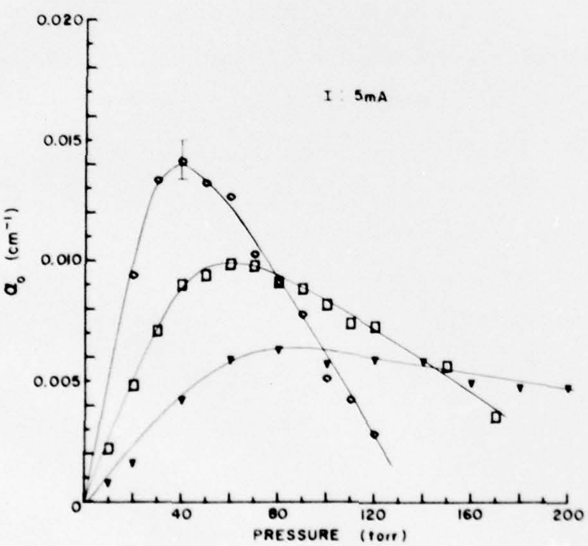

FIGURE 3 - Small-signal-gain coefficient versus pressure for various sealed-off CO_2:Xe:He mixtures: o [40:4:56], □ [20:4:76], ∇ [10:4:86]

and that an equilibrium was rapidly reached following the onset of the current. Studies conducted in low-pressure tubes have shown that dissociation increases with the current and with the reduced field strength, E/p, (Ref. 17). The dissociation of about 60% (Refs. 15-16) of the CO_2 molecules has been measured at total pressures between 10 and 20 torr and current densities around 10 mA/cm^2. The exact amount of dissociation in our tubes was not known but it is expected to be non negligible.

The measured gain coefficient as a function of total pressure is shown in Fig. 3 for 3 different CO_2:Xe:He mixtures. For these measurements, the total current was maintained at 5 mA (2.5 mA in each discharge channel) and the temperature at 17^{o}C. In all cases, the gain coefficient rose with the working pressure, reached a maximum and began to fall. As already observed in a 1.5-mm-diameter tube (Refs. 6, 19), 3 main features appeared from these results. First, the gain peaked at lower pressures for mixtures richer in CO_2; secondly, the addition of He shifted the maximum gain toward higher pressures and lowered its maximum value; and finally, the gain coefficient was almost independent of pressure at a high He concentration. Figure 4 shows in more detail the variation of the peak-gain coefficient α_o^{max} and the pressure at which it occurred versus the CO_2 concentration. At CO_2 concentrations of 40% and higher, α_o^{max} leveled at about 1.4% cm^{-1}. It is seen that the optimum total pressure varies roughly as $1/[CO_2]$, implying that α_o^{max} occurs at a constant CO_2 partial pressure of ≃ 15 torr in a 2-mm bore.

The observed behavior fits the prediction of the model published by Cohen (Ref. 20). At a total pressure lower than ≃ 50 torr, the gain line is Doppler-broadened and the initial rise of the gain is governed by the increase of the number of active molecules. At higher pressures, the gas temperature increases with the power dissipated in the discharge, and the inversion decreases. The lower sensitivity of

the gain on pressure in a He-rich mixture is attributed to the cooling effect of He which, as in conventional CO_2 lasers, enhances the thermal conductivity of the gas and makes it less sensitive to an increase of the dissipated electrical energy.

The effect on the small-signal-gain coefficient of the addition of CO without O_2 is shown in Fig. 5 where gain versus pressure of a 30:4:66, CO_2:Xe:He mixture is compared to the gain of a 20:10:4:66, CO_2:CO:Xe:He mixture. It is seen that the replacement of some CO_2 by CO increased the high-pressure portion of the curve while the maximum gain α_o^{max} stayed close to that of the medium richer in CO_2. Mixtures with 10% of CO_2 exhibited a similar trend. This appears very promising as it allows a larger gain at high pressure and, consequently, a better power extraction from the laser medium and a larger tuning range. Although physical mechanisms behind this behavior are not well understood, it appears that 2 phenomena may be responsible for the observed behavior. First, at low pressure where dissociation is more important, the addition of CO in proportions greater than the stoichiometric ratio may favor a backward process of the reaction [1] leading to less dissociation of CO_2. Secondly, at high pressure, the CO is expected to quench the 01^10 level of CO_2 through which the lower laser level deexcites (Ref. 21); this role of CO would then be similar to the one of He in allowing a better energy dissipation.

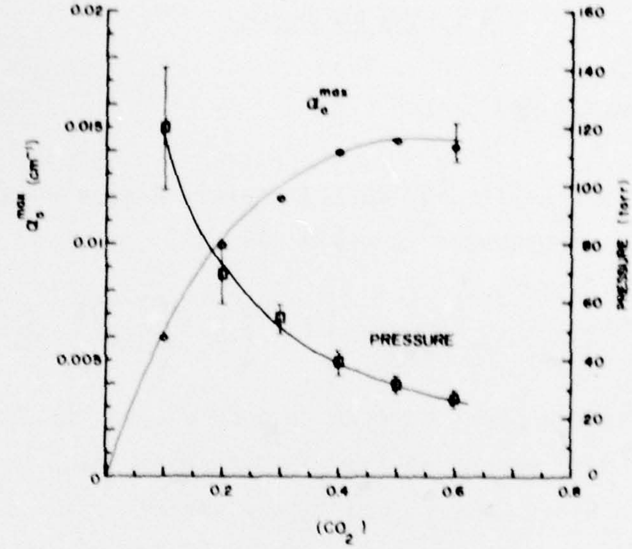

FIGURE 4 - Maximum small-signal-gain coefficient α_o^{max} and optimum pressure versus CO_2 concentration in a CO_2:Xe:He mixture. The Xe concentration was kept constant at 4%.

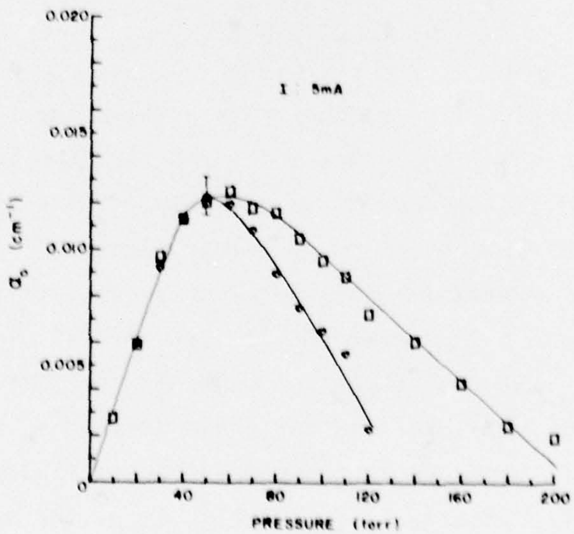

FIGURE 5 - Small-signal-gain coefficient versus pressure of a CO_2:CO:Xe:He mixture of 20:10:4:66 [□] as compared to the gain of a CO_2:Xe:He mixture of 30:4:66 [o]

4.0 OUTPUT POWER

4.1 Theoretical background

In the homogeneous-line-broadened regime, Rigrod's power equation for the laser output power is (Refs. 22, 23)

$$P(\nu) = \frac{I_s(\nu_o)\ A\sqrt{R_1}\ T_2\ \alpha_o\ L}{(\sqrt{R_1} + \sqrt{R_2})\ (1-\sqrt{R_1R_2}))} \left[1 + \left(1+4\left(\frac{\nu-\nu_o}{\Delta\nu}\right)^2\right)\frac{\ell n(\sqrt{R_1R_2})}{\alpha_o L}\right] \quad [2]$$

where A is the effective cross section ($\approx 0.65\ a^2$ for the EH_{11} mode assuming that the waist radius of the gaussian beam which best fits the mode amounts to 0.6435 a); R_1 and R_2 are the effective reflectivities of the end mirrors; T_2 is the transmittance of the output mirror assumed to be mirror 2; L is the gain length; ν_o is the center frequency of the lasing transition and $\Delta\nu$ is the full line width at half maximum assuming a Lorentzian line shape. The parameter $I_s\ (\nu_o)$ is the saturation intensity at the line center and is given by

$$I_s\ (\nu_o) = \frac{h\nu_o}{\sigma_o\ (t_u + t_\ell)} \quad [3]$$

where h is Planck's constant, σ_o is the cross section for the stimulated emission at the line center and t_u, t_ℓ are the lifetimes of the upper and lower lasing levels respectively. These lifetimes can be decreased by molecule-molecule or electron-molecule collisions in the gas volume and by wall deactivation. At sufficiently high pressure ($p \geq 60$ torr in a 2-mm-diameter tube) (Ref. 24), the volume quenching rate becomes the most important mechanism so that $(t_u + t_\ell)^{-1}$ increases linearly with pressure. As the cross section σ_o also increases linearly with pressure in the homogeneously line-broadened regime, the saturation parameter $I_s\ (\nu_o)$ varies as p^2 (Refs. 24, 6).

Assuming that there are no losses other than coupling ($R_1 = 1$, $T_2 = 1 - R_2$), eq. 2 can be written, at the line center,

$$P(\nu_o) = \alpha_o I_s (\nu_o) AL \left(1 + \frac{\ell n \sqrt{R_2}}{\alpha_o L}\right) \quad [4]$$

From this equation, it is seen that 2 factors determine the output power of the laser. On the one hand, there is a certain maximum amount of power available in the gain medium that depends on the medium inversion. If the gain is assumed much greater than the losses ($\alpha_o L >> \ell n \sqrt{R_2}$), this limit is obtained from eq. 4 by

$$P_\ell (\nu_o) = I_s (\nu_o) \alpha_o AL \quad [5]$$

which becomes in the high-pressure regime

$$P_\ell(\nu_o) \propto p^2. \quad [6]$$

On the other hand, the efficiency for extracting that power is given by the factor $(1 + \ell n \sqrt{R_2}/\alpha_o L)$ and depends on the ratio $\ell n \sqrt{R_2}/\alpha_o L$ so that efficient operation can be achieved only when the small-signal gain is sufficiently large. For given losses, a lasing mixture that optimizes the product of both factors has to be found in order to maximize the output power of the laser.

4.2 Experimental

Small-signal-gain measurements have shown that He rich mixtures have higher gain at high pressures. In order to show the variation of the available power with the gas mixture composition, we have plotted in Fig. 6 the product $\alpha_o^{max} p_{max}^2$ versus the CO_2 concentration in a CO_2:Xe:He mixture. It is seen that because of a higher optimum pressure, the available power increases with a reduction of the CO_2 concentration. However, as the small-signal-gain coefficient

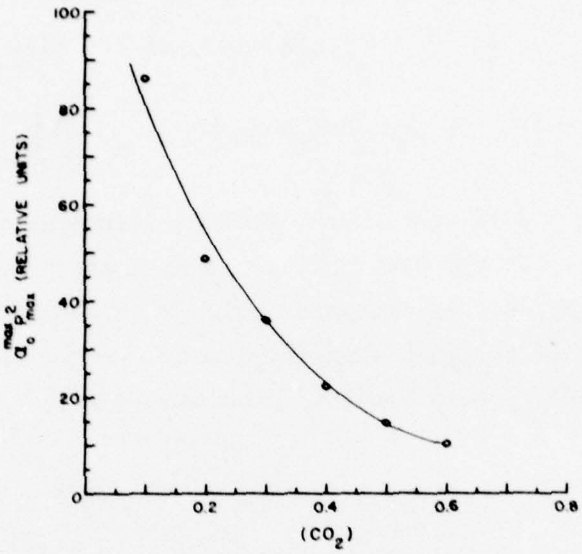

FIGURE 6 - Variation of the product α_o^{max} p_{max}^2 versus CO_2 concentration in a CO_2:Xe:He mixture at a current of 5 mA

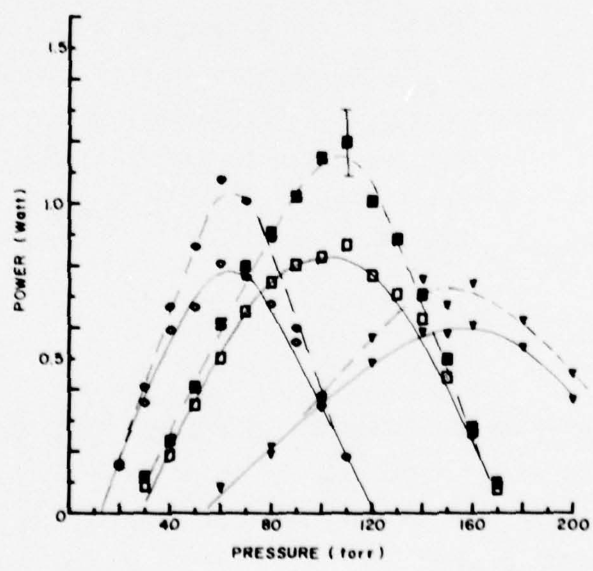

FIGURE 7 - Variation of the output power versus pressure for different CO_2:Xe:He mixtures; o, ●: [40:4:56]; □, ■ : [20:4:76]; ▽, ▼, [10:4:86]. o, □ , ▽ are with a total current of 5 mA, ●, ■ , ▼, with a total current of 7 mA.

of these mixtures is lower, power extraction is expected to be less efficient. Although the optimum mixture varies with the tube losses, one can state as a general tendency that in a tube with high losses, CO_2-rich mixtures should provide maximum power whereas mixtures richer in He should be preferable in low-loss tubes.

Laser output power versus total pressure for various CO_2:Xe:He mixtures is shown in Fig. 7 for 5-and 7-mA total discharge current (2.5 and 3.5 mA per discharge arm) when a 96% reflecting mirror is used as coupling mirror. For these experiments, the laser tube was water cooled at 17°C and the discharge length was 9.5 cm. It is seen that the laser output clearly peaked at pressures well above the optimum pressure for a peak gain: this demonstrates the increase saturation parameter I_s with pressure. Unlike the small-signal-gain, the output power increased with the discharge current, particularly at pressures where the output is near optimum. This indicates an increase of the saturation parameter with current, as has already been measured (Ref. 24). For most mixtures, the current giving the highest output power was not reached as it was beyond the limits of the available power supplies.

Figure 8 shows the effect of replacing some of the CO_2 by CO in a 30:4:66, CO_2:Xe:He mixture at a total current of 5 mA. It is seen that the addition of CO led to a significant improvement of the output power with a displacement of the maximum pressure toward higher values. This resulted from an increase of the small-signal-gain coefficient at high pressure, as seen in Fig. 5, and of the p^2-variation of the available power. The exact optimum mixture will then depend strongly on the laser cavity losses, but the addition of CO seems to lead to a greater efficiency.

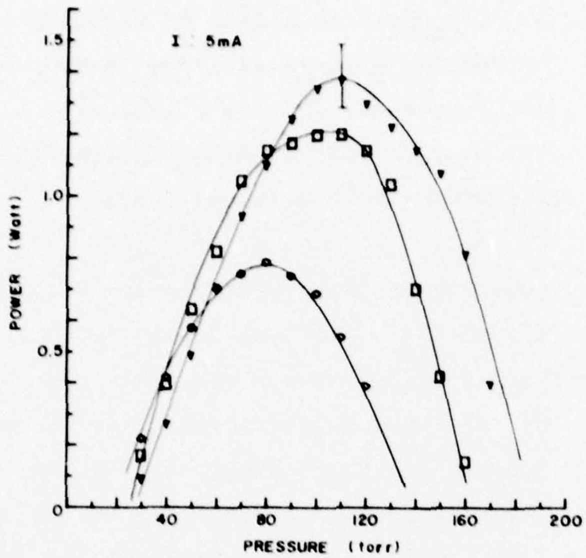

FIGURE 8 - Variation of the output power versus pressure when a part of the CO_2 is replaced by CO in a CO_2:CO;Xe:He mixture: o, [30:0:4:66]; □, [20:10:4:66]; ∇, [10:20:4:66].

An output power as high as 1.7 W was obtained at 7 mA at a pressure of 110 torr in a CO_2:CO:Xe:He mixture of 10:20:4:66, which corresponds to a power per unit length P/L of 0.18 W/cm. This value should be compared to the unit-length power extraction of 0.2 W/cm and 0.31 W/cm obtained by Abrams and Bridges (Ref. 6) and by Hall et al (Ref. 7) respectively. Abrams' measurements were conducted in a 18-cm × 1.5-mm tube with a He:CO_2 mixture. For fixed losses, a longer tube allows a better extraction at a higher pressure and, as the available power increases as p^2, leads to a more efficient operation. Hall's results were also obtained in a longer tube (20 cm × 2 mm) at a discharge current of 11.2 mA and in a CO_2:N_2:Xe:He gas mixture.

Finally, the addition of N_2 improved the pumping efficiency of the upper CO_2 lasing level (Ref. 25) but, as discussed later, resulted in a shorter lifetime in sealed-off operation.

5.0 TUNING RANGE

5.1 Theoretical background

Matters of particular importance in systems which use heterodyne detection are tuning range, frequency stability and state of polarization of the laser output. The frequency domain in which the laser oscillates is obtained from eq. 2:

$$2(\nu_\ell - \nu_o) = \Delta\nu \left(\frac{2\ \alpha_o L}{\ell n (R_1 R_2)^{-1}} - 1 \right)^{1/2} \qquad [7]$$

where ν_ℓ is the offset frequency at which the laser oscillation ceases. For a CO_2:He mixture, the Lorentzian linewidth is given by (Ref. 26):

$$\Delta\nu = 7.58\ ([CO_2] + 0.6\ [He])\ P(MHz) \qquad [8]$$

where p is the pressure in torr and [CO_2], [He] are the CO_2 and He proportions respectively. For a standard 30:70 mixture, the pressure broadening rate amounts to about 5.5 MHz/torr. It is seen from eq. 7 that the tuning range is very sensitive to the small-signal-gain coefficient and to the mirror reflectivities (which include the waveguide losses). An exact prediction of the tuning range of a given laser appears difficult. A phenomenological analysis by Degnan (Ref. 22) has shown that maximizing the output power of a given laser by varying the pressure simultaneously maximizes the tuning range. However, mirror reflectivities that maximize the output power will not optimize the tuning range that increases monotonically with R_1R_2.

5.2 Experimental

In order to measure the frequency and polarization characteristics of our laser, the completely reflecting mirror was mounted on a PZT translator. For those measurements, a CO_2:Xe:He mixture of 30:4:66 was used and the current was held at 4 mA. No polarizing element was included in the laser cavity. The coupling mirror was specified to have a reflectivity of 96%. Figure 9(a) illustrates the signature of the laser output at a pressure of 60 torr as the cavity length is swept across its free spectral range of 1 GHz by the application of a linear voltage ramp to the PZT translator. As many as 10 lines oscillated. Because of lasing action on the R16 and P24 lines, the tuning range of the P20 line was limited to 160 MHz. Analysis with an external ZnSe window mounted at the Brewster angle showed that the output was linearly polarized as expected from calculations for the EH_{11} mode (Ref. 8). However, further analysis has indicated that the electric field E vector rotated, most of the time by $\pi/2$ steps, as the laser cavity was tuned through its free spectral range. This is illustrated in Fig. 9(b) and 9(c) where the horizontal and vertical components of E are displayed versus the cavity length. It is seen that the E rotation can occur anywhere in the free spectral range. Changes in the mirror alignment never led to a constant orientation of the polarization under all conditions.

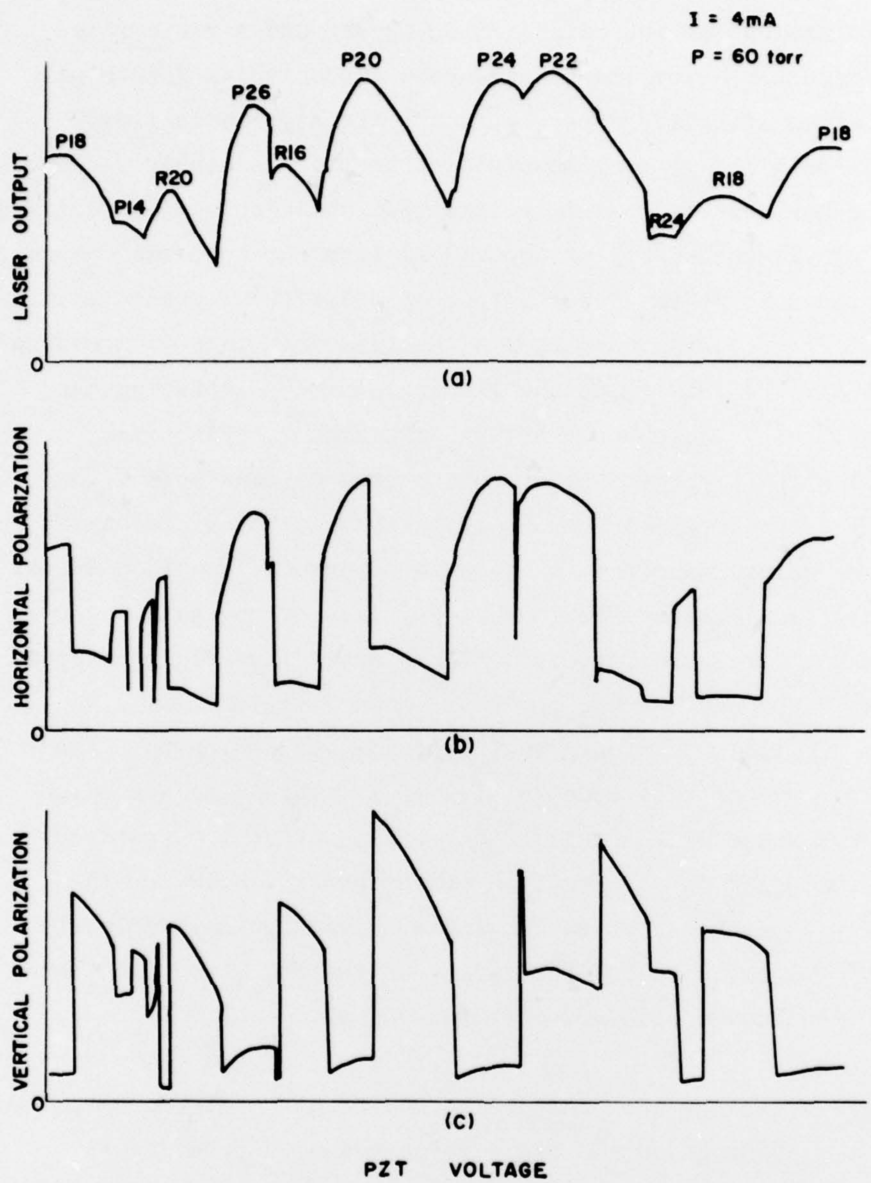

FIGURE 9 - Laser output power versus PZT translator tuning at 60 torr without dispersive and polarizing element in the cavity. The CO_2:Xe:He gas mixture was 30:4:66 and the coupling mirror had a reflectivity of 96%. (a) total output, (b) horizontal polarization component, (c) vertical polarization component

As variations of the polarization appear undesirable in a heterodyne receiver, experiments have been conducted to determine the polarization stability after replacing the high-reflectivity mirror by an original grating mounted in the Littrow configuration. In a first experiment, a 75-ℓ/mm blazed grating which had a specified efficiency of 95% was placed at about 5 mm from the tube end. Figure 10 shows the signature of the laser output at 3 different pressures. It is seen that at 60 torr, the number of oscillating lines was reduced to 6 as compared to 10 without the grating, thereby improving the tuning range. As a consequence of the much higher reflectivity of the grating for E perpendicular to the grooves, analysis with the external Brewster window confirmed a linearly polarized output all over the tuning range. At a higher pressure, a reduction in the number of oscillating lines followed a decrease of the gain. In the maximum-gain pressure region, a higher order linearly polarized mode, probably the hybrid $EH_{-1,1} + EH_{3,1}$ mode (Ref. 8), was also observed to oscillate at proper tuning of the cavity length. The relative amplitude of this mode in Fig. 10 is misleading since it has a doughnut shape with a null on the axis so that the centered detector intercepted only a fraction of the power. However, in our operating conditions, it was possible to extinguish completely this mode by proper tuning of the cavity on the $EH_{1,1}$ mode so that no beating frequency was observed at the output.

Figure 11 illustrates the pressure dependence of the output power and of the tuning range on the P20 line as measured from curves similar to those in Fig. 10. During these measurements, it has been verified that only one line at a time was oscillating. It is seen that the maximum tuning range occurred at a pressure slightly higher than the maximum output power in contradiction with Degnan's conclusions. A closer examination of Fig. 10 indicates that lasing of the P24 and P18 lines prevented full coverage of the possible tuning range and was responsible for this apparent discrepancy. A tuning range of 360 MHz at 80 torr is calcultated from eq. 7 assuming

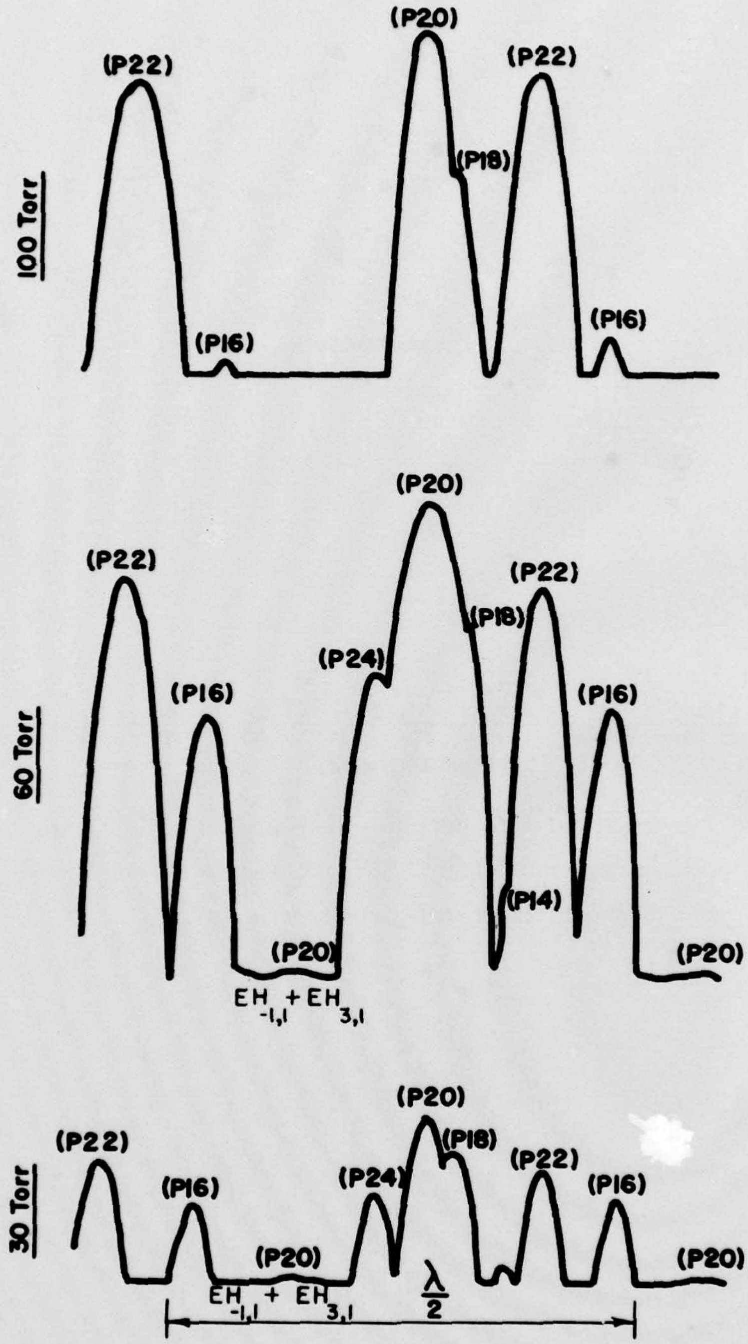

FIGURE 10 - Tuning characteristics for various total gas pressure when the completely reflecting mirror was replaced by a 75-ℓ/mm grating

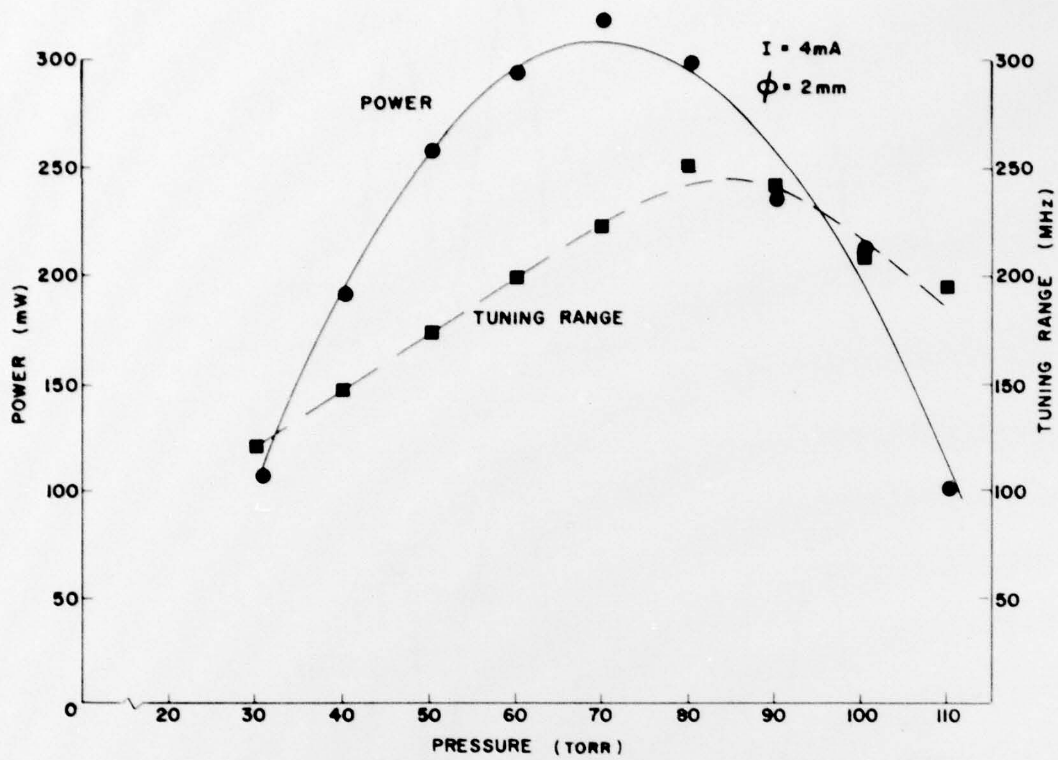

FIGURE 11 - Variation of the output power and of the tuning range versus pressure for a 30:4:66 mixture when a 96% R mirror and a 75-gr/mm grating forms the cavity

a signal-gain coefficient of 0.9% cm^{-1} as seen in Fig. 5 for a similar mixture, a coupling-mirror reflectivity of 96% and a grating efficiency of 94% (absorption in the ZnSe sealing window was included in determining this efficiency). This value is considerably larger than the 250 MHz measured. Besides the limitation imposed by the lack of dispersive power of the grating, and the oscillation of the P18 and P24 lines, the overestimation of the tuning range may be caused by an underestimation of the tube losses. This is supported by the observation of a decrease of the output power that followed arcing between the center cathodes prior to the above measurements.

In conclusion, the above results indicate that a polarization element must be included in the cavity in applications like the heterodyne reception, where the orientation of the E vector must be kept constant. While this element can be simply an internal Brewster window, it has been found that the use of a grating determined the polarization orientation in all conditions and improved the tuning range by limiting the number of oscillating lines. However, with a discharge length of about 10 cm, a 75-ℓ/mm grating has not enough dispersive power to completely extinguish the neighboring lines and, where tuning range is important, a grating with 135 to 150 ℓ/mm should be used and losses should be minimized by using either a coupling mirror with a higher reflectivity or a more efficient grating.

6.0 SEALED-OFF OPERATION

In order to effectively exploit the advantages of waveguide lasers in size and frequency capabilities, it is desirable to use a sealed-off system and thereby avoid bulky gas circulating apparatus as well as turbulence and fluctuating pressure that may cause frequency instabilities in flowing-gas systems. Mechanisms reponsible for the limited lifetime of sealed-off CO_2 lasers are primarily the dissociation of CO_2 according to reaction [1] followed by the absorption of the O_2 on the tube and cathode surfaces and by the sputtering products (Ref. 15). Depletion of the oxygen results in a displacement of the equilibrium, in a decrease of the CO_2 content and, ultimately, in the extinction of the laser oscillation. To achieve long-life operation, care must be taken to minimize the dissociation rate and to use chemically inert cathode and wall material. Furthermore, cathodes must have a very low sputtering rate in the presence of the particular mixture used, and the sputtering products must contain an absolute minimum (Ref. 27) of negative ions to minimize deposits in the anode region.

Lifetime tests have been performed on tubes similar to the one shown in Fig. 1. For these tests, the end mirrors were epoxied on stainless-steel holders fixed to the tube ends. Each tube has been checked to have a He leakage rate of less than 10^{-9} atm - cm^3/second. The anodes were made of sharpened (60^o) tungsten pins press-fitted into stainless steel cups. To minimize the dissociation rate that increases with the discharge current (Ref. 17), lifetime tests were performed at 2 mA per discharge arm. As the addition of small quantities of Xe has been found to reduce the E/p value, to diminish the number of CO_2, O_2 and CO ions, to decrease the oxidation rate and consequently, to increase the sealed-off lifetime (Ref. 28), 4% of Xe was added to form a CO_2:Xe:He gas mixture of 30:4:66. During these tests, the stainless-steel tubing used as filling port represented a gas reservoir of about 10 cm^3.

The best results have been obtained with cathodes made of 90% Pt and 10% Ir or with pure Cu (Ref. 29) as shown in Figs. 12 and 13, respectively. Lifetimes longer than 600 h have been achieved in each case but results could not be reproduced. Analysis of the history of each tube showed no relation between the number of previous fillings and the maximum lifetime. In the case of Pt-Ir cathodes, the maximum lifetime was obtained with the second fill and in the second case, (Cu cathodes), with the first fill. In all cases, the output power increased during the first hours of operation and then started to decrease. Usually, a faster increasing rate was followed by a faster decreasing rate in agreement with the hypothesis of a faster oxidation. The time history of the power also agreed with the hypothesis of a gradual depletion of the O_2 content; replacement of some of the CO_2 by CO has been found to lead to an improvement of the power output (Fig. 8). Attempts to get longer lifetimes by using a larger gas reservoir have not been successful. This was attributed to the use of Kovar anodes to join the reservoir to the laser. Furthermore, life tests with mixtures containing N_2 have never resulted in lifetimes exceeding 40 h with the Cu or Pt-Ir cathodes. Nevertheless, operation times of the order of 300 h can be expected at that stage allowing semi-sealed-off operation with filling about every month. It is also concluded that a CO_2:Xe:He mixture, even if it does not optimize the output power, will lead to a longer tube life than the more efficient CO_2:CO:Xe:He mixture as a result of the gradual depletion of the O_2 and, consequently, the equilibrium CO_2 content. Attempts to increase the operational life are in progress.

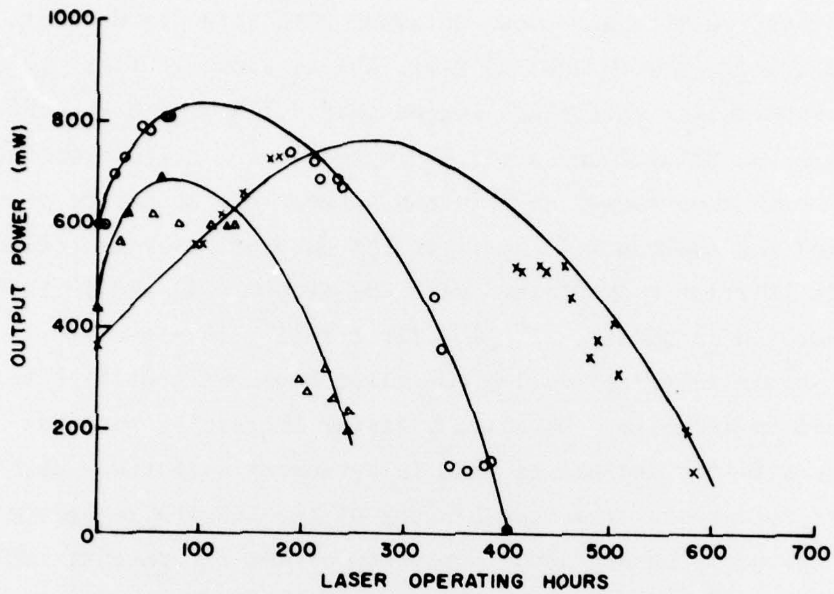

FIGURE 12 - Sealed-off lifetime of a 9.5-cm-long waveguide laser with Pt-Ir cathodes; o, X, ∇ represent respectively first, second and third fill data.

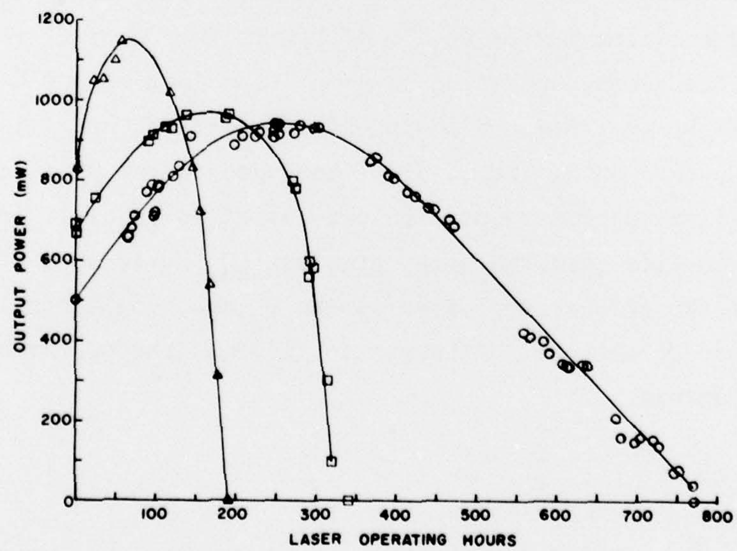

FIGURE 13 - Sealed-off lifetime of a 9.5-cm-long waveguide laser with Cu cathodes; o ∇,□ represent respectively first, second and third fill data.

7.0 CONCLUSIONS

We have developed a convenient assembling technique that allows construction of rugged waveguide CO_2 laser tubes. Analysis of the operating characteristics has shown that a specific output power of 0.18 W/cm was possible in a 9.5-cm-long discharge and that larger values are expected in longer discharges. Extreme care must be taken to prevent any arcing that very rapidly deteriorates the tube and dramatically lowers the output power. Because a polarizing element is required in the cavity to set the orientation of the electric field, it was found that the use of a grating determines the polarization and increases the effective tuning range. Low-loss ($< 5\%$) and high-dispersion ($\simeq 135$ gr/mm) gratings appear necessary to achieve all the expected frequency-stability and tunability performances of CO_2 waveguide lasers. Long sealed-off operation requires extreme care in the tube assembly and in the choice of the cathode material and other tube components. Operation lifetimes of 300 h are now possible. Longer life requires further analysis of the complex dissociation processes involved but an operating heterodyne local oscillator can already be designed.

8.0 ACKNOWLEDGEMENTS

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